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1 **A farm level approach to explore farm gross margin effects of soil organic carbon**
2 **management**

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Abstract

This paper investigates farm gross margin effects of management measures aimed at enhancing soil organic carbon (SOC) stocks to maintain soil fertility while providing important ecosystem services. An optimising farm level model, ScotFarm, is used to investigate the farm gross margin effects of selected SOC management measures for arable farms in Scotland (UK) and Aragon (Spain). The sensitivity of model results to effects on crop yields and costs of production is tested for each measure. The results suggest that considerable regional differences in the financial viability of SOC measures exist. Tillage management is the only measure with positive effects on farm gross margins of Scottish farms at baseline levels of yield effects and input costs. In the case of farms in Aragon, Spain, fertiliser management, crop rotations (with legumes) and tillage management (in later years) show improvements in gross margins. Residue management is estimated to have a negative effect on farm gross margins for both Scottish and Spanish crop farms. Results of the sensitivity analysis indicate that effects of SOC management on farm gross margins are more sensitive to a change in crop yields than to changes in input costs. The findings point to further research needs with respect to the trade-offs between yield effects and changes in input costs arising from the adoption of SOC management measures, and have implications for agricultural policy design aimed at enhancing SOC stocks under a changing climate.

Key words:

soil organic carbon, soil management, farm level modelling, arable farming, trade-offs, profitability

Highlights:

- A farm level model is used to assess effects of different SOC management practices
- Analysis of the trade-offs between effects on yield and input costs on farm gross margins (GM)
- GM effects: more sensitive to crop yield changes than to changes in input costs
- Maximum positive effect on GM greater for Aragon (Spain) compared to Scotland (UK)
- In total three SOC measures are found to be relatively robust to assumptions made

1 **1. Introduction**

2 The stocks of Soil Organic Carbon (SOC) interact in a complex manner with soil
3 properties and functions that ultimately affects the provision of ecosystem services
4 (Robinson et al. 2013; Dominati et al. 2010). Management of SOC in arable agricultural
5 systems can affect the productive capacity of land as a final ecosystem service by
6 improving the growth conditions for crops and therefore yields, and by increasing
7 nutrient use efficiency that may affect the amount of fertiliser input required for
8 optimal plant growth (e.g., Luxhøi et al. 2007; Pan et al. 2010). These effects are related
9 to intermediate services that are affected by soil organic matter stocks and flows,
10 including the provision of plant available nutrients, the control of erosion/loss of
11 topsoil, the provision of a platform for (root) growth, the provision of a moisture regime
12 that is suitable for plant growth, levels of biological diversity influencing pest/disease
13 control, and the provision of a habitat for soil-based pollinators (Glenk et al. 2013).
14 Additionally, management of SOC has been associated with a wide range of potentially
15 beneficial (co-)effects, notably the potential to contribute to climate change mitigation
16 via soil-based carbon sequestration, to help improve water quality at catchment level,
17 and to enhance sub-soil and aboveground biodiversity (Freibauer et al. 2004; Feng and
18 Kling 2005; Smith et al. 2007a; Glenk and Colombo 2011).

19 Despite an increasing policy interest in increasing SOC stocks (EC 2011), there is a lack
20 of evidence on the magnitude of private benefits of changes to SOC management to
21 farmers. Such evidence is needed, however, to provide meaningful guidance to farmers
22 and to inform considerations of policy support aimed at enhancing the uptake of SOC
23 management measures. This paper contributes to filling this evidence gap. The objective
24 of this study is to investigate the effects on farm gross margins of adopting suitable SOC

25 management measures for a number of representative arable farms in two EU-regions
26 (Scotland, UK; Aragon, Spain).

27 Additionally, this study aims at assessing the robustness of farm gross margin effects to
28 changes in effects on nutrient availability and yield. Nutrient availability and yield
29 effects are of great relevance in the context of moving to sustainable agricultural
30 systems that provide food security in the mid- and long term (Kahiluoto et al. 2014),
31 where food demand is expected to increase and substitution of organic fertilisers
32 through inorganic ones may become increasingly challenging (Cordell et al. 2009).

33 Effects of SOC management on crop production are climate, soil and crop specific
34 (Sánchez et al. 2016a), and therefore differ between the investigated SOC management
35 measures, which include, for example, cover crops, residue management, and zero and
36 reduced tillage. Within the SOC management measures and under given environmental
37 conditions there is considerable uncertainty regarding their effect on nutrient
38 availability, yield and other effects on variable costs of farming including pest control
39 and changes in farming operations, which are highly dependent on spatial context and
40 farm characteristics (Morris et al. 2010; Rickson et al. 2010). This paper uses plausible
41 ranges of key parameters regarding the effects on nutrient availability, yield effects, pest
42 control and farming operations derived from expert knowledge and guided by available
43 literature. Data on plausible ranges of effects then enter a sensitivity analysis using an
44 optimising farm level model (ScotFarm) to reveal the robustness of SOC management
45 measures to changes in input costs and yield effects. High levels of variability in farm
46 gross margin effects can act as a barrier to uptake especially by risk averse farmers.

47

48

49 **2. Methodology**

50 **2.1 Model structure**

51 The profit maximising dynamic farm level model ScotFarm (Shrestha et. al. 2014) is
52 used to investigate farm gross margin effects of different SOC management measures
53 for representative crop farms in each of the two EU study regions (Scotland, UK; Aragon,
54 Spain). The model follows the classic linear programming structure as provided in
55 equation (1) below.

$$56 \quad \text{Max } z = (p - c) * x + SFP \text{ subject to } A * x \leq R \text{ and } x \geq 0, \quad (1)$$

57 where z is the farm gross margin, x is the quantity of each crop produced on farm per
58 hectare, p is the revenue collected from activity x , c are the costs incurred to produce
59 activity x , SFP is the farm payment, A is an input-output coefficient of activity x , and R is
60 a limiting farm resource.

61 The model is based on farming system analysis (Fresco 1988; Keating and McCown
62 2001), where all existing farm activities and interactions between farm structure,
63 management, activities and management are taken into account. The model structure is
64 represented in Figure 1 below.

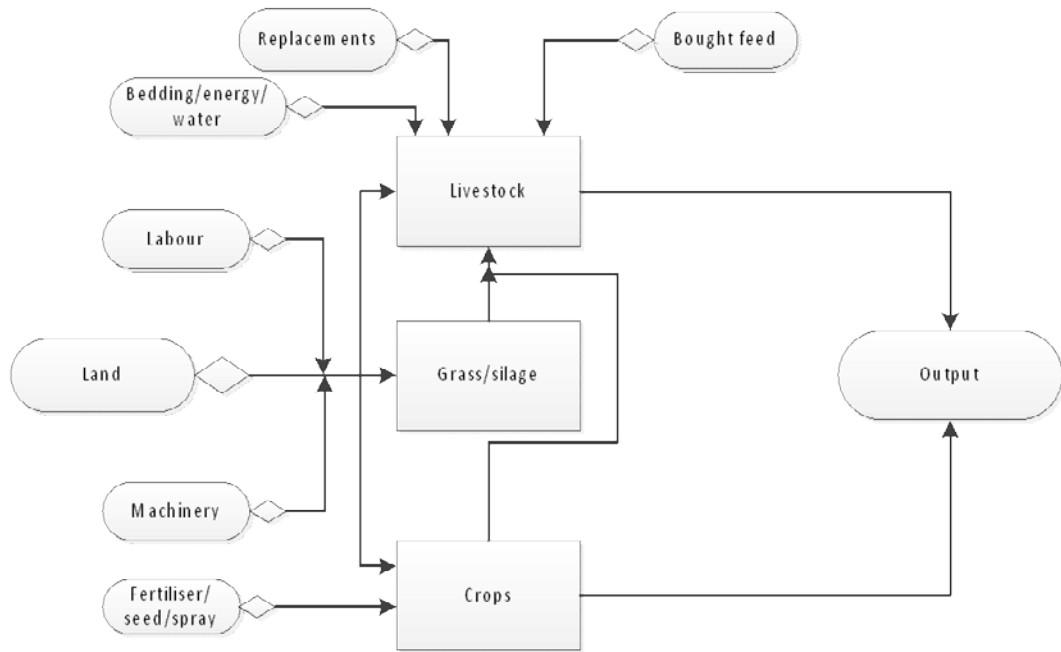


Figure 1. A schematic diagram of ScotFarm

65
66

67 It is assumed that farmers are profit oriented and maximise farm gross margins within a
 68 set of limiting farm resources. The farm gross margin is comprised of the accumulated
 69 revenue from the final products of different farm activities and from farm subsidy
 70 payments, minus the cost incurred for inputs for the farming activities. ScotFarm is an
 71 optimising model, hence it should be noted that the results provided by the model are
 72 based on achieving all farm activities and farm management to the optimal level.

73 There is an emphasis on the crop component of the model in this study. The model
 74 encompasses crop production that is limited within fixed available land (Equation 2).

75
$$ALAND \geq \sum_{c=1}^n ACROP_c \quad \forall f, y \quad (2)$$

76 where ALAND is the total area of arable land available for farm f in year y and ACROP is
 77 the land area under crop c .

78 All major crops in each region are available for selection in the model. The area of total
 79 farm land is fixed (ALAND), but the model re-allocates arable land under each of the
 80 crops from year to year. The area under each crop is assumed to be at least 50% of the

81 area under the same crop in the previous year to facilitate a smooth transition in change
82 in crop activity. The model selects the most profitable crop based on revenues collected,
83 which is determined by yield and the price of the crop, and the costs of production
84 incurred (Equation 3).

$$85 \quad C\rho = \sum_{c=1}^n ACROP_c * (YIELD_c * price_c - costs_c) \quad (3)$$

86 where $C\rho$ = crop gross margins, $ACROP$ = land cover, $YIELD_c$ = crop yield and $costs_c$ =
87 costs of production (fertiliser use, sprays, seeds and machinery costs) for each crop c .

88 The model is used to analyse the effect on farm gross margins of changes in crop yields
89 and costs of production for a range of SOC management measures and representative
90 farm types in each of two study regions. The model adjusts farming activities based on
91 the changes in crop yields and costs of production to optimise the farm gross margin
92 when SOC management measures are available.

93 All the activities are constrained by labour availability to comply with labour
94 requirements. The labour requirement for each activity is based on literature and
95 expert knowledge. Total labour available on farm is derived from existing information
96 on family labour units available in farm level data. Family labour is assumed to be
97 skilled labour, providing up to 2,200 hours per labour unit each year. Apart from family
98 labour, farm activities also use contract costs (labour and machinery), which are crop
99 specific and included in the variable costs of crop production. The model assumes
100 contractors are available all year round and hence seasonal variability of the labour
101 requirement is not considered in the model.

102 Grass and livestock production are additionally considered for Scotland (UK), because
103 many Scottish crop farms also have sheep/beef animals and use some of the crops
104 produced to feed animals. Grassland can be transformed to arable land and vice versa

105 based on the profitability of each of the production system. For livestock feed, besides
106 grazing and grass silage, each farm types has a minimum level of concentrate fed to the
107 animals on farms (based on existing data). This requirement of concentrate feed is first
108 fulfilled by the cereal crop produced on farm and then if required more brought in from
109 the market. Farms in Aragon (Spain) primarily focus on arable production but may also
110 keep pigs. There is no direct link between pig production and arable production,
111 because farmers usually feed their animals with concentrate obtained from the market.
112 Therefore, a pig component was not developed for modelling farms in Aragon.

113 The model is run over a period of 21 years. The input data for the first year is based on
114 available farm level data. For subsequent years, farm activities are based on the
115 activities in the previous year and costs, prices and availability of farm resources for
116 that particular year. For example, for the livestock component the number of year-old
117 beef animals depends on the number of calves born and calves sold in the previous year.
118 The area under each crop in a particular year is based on the number of livestock in that
119 year (if it is a mixed farm) and the area under that crop in the previous year. Changes in
120 costs and prices for each year are determined using price indices taken from a partial
121 equilibrium model FAPRI (AFBINI, 2012; Binfield et al. 2015). Model results are
122 obtained for each year but results for the first and last three years are discarded to
123 minimise initial and terminal effects of linear programming (Ahmad 1997; Shrestha
124 2004). The results for the remaining 15 years are presented in 5-yearly averaged
125 figures.

126 The model was run under a 'baseline' scenario for each region and farm type, where
127 crop yields and input costs are based on farm level data, and a number of soil organic
128 carbon management (SOC) scenarios based on the specified SOC management

129 measures. To infer the effect of the SOC management measures on farm gross margins,
130 the model results of the SOC management scenarios are compared to results of the
131 baseline scenario. The input parameters used for the changes in crop yields and input
132 costs under the SOC management measures are based on literature and observed data if
133 available, and adjusted using expert knowledge to allow for estimates that better reflect
134 the heterogeneity in environmental condition in the case study regions. Details on input
135 parameters are provided in Section 2.5.

136 To analyse the effects of SOC management measures on farm gross margins, three sets
137 of parameters for changes in yield effects and input costs were employed that represent
138 the plausible range that each can take across the range of farms within the two regions.
139 The first set of parameters reflects typical farming conditions (**Y** for crop yield and **C** for
140 input costs). The remaining two sets of parameters will be used to investigate the
141 sensitivity of farm gross margin effects to all four combinations of lower bound (**Y_{min}**
142 and **C_{min}**) and the upper bound (**Y_{max}** and **C_{max}**) values of the plausible range.

143 The results across the four resulting cases demonstrates the relative trade-offs between
144 yield effects and changes in input costs associated with each management measure. This
145 provides important insights into the robustness of SOC management measures to result
146 in positive changes in farm gross margins.

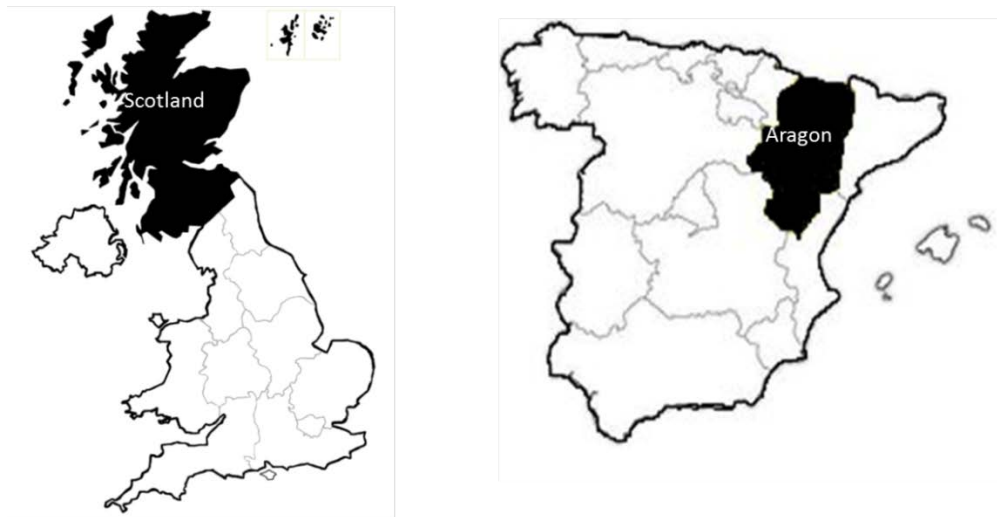
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148 **2.2 Study regions**

149 As part of the EU FP7 project SmartSOIL¹, case study regions have been selected to
150 support the collation of data in different bio-geographic and social-economic
151 agricultural areas, to develop scenarios for different farming systems and regions in

¹ For details see <http://smartsoil.eu/>

152 Europe and to engage and consult with stakeholders at local and regional level (farmers,
153 farm advisory and extension services, policy makers etc.). The regions included in this
154 study are Scotland, UK and Aragon, Spain (Figure 2). The two regions reflect different
155 agro-ecological conditions and allow a first insight into the regional heterogeneity of in
156 the potential of SOC management measures across Europe. There is an increasing
157 interest in management practices that will improve the soil carbon (Scottish
158 Government, 2005; Sánchez et al. 2016a). A brief overview of the study regions are
159 provided below.



160

161 **Figure 2.** Study region Scotland, UK and Aragon, Spain

162 2.2.1 Scotland

163 Arable farms in Scotland are mostly concentrated in the East covering around 0.6
164 million hectare of land. Scotland has a maritime climate, and is influenced by the
165 Atlantic gulf stream (the average annual rainfall for the arable area is between 400-900
166 mm, and the mean average temperature is between 6 °C to 7 °C). As shown in Table 1,
167 the average arable land area for these farms is 132 ha. These farms also have 64 ha of
168 grassland on average. The main crops produced on farms are winter wheat, spring
169 barley, spring oats and break crops, for example winter oilseed rape. Potatoes and other

170 horticultural crops are not included in the study as they are not targeted by the SOC
 171 management measures considered in the study. Agricultural management is largely
 172 based on conventional tillage and the use of fertilisers and pesticides.

173 **Table 1.** Characteristics of arable farming in Scotland (UK) and Aragon (Spain)

Region	Arable area (ha)	Grass area (ha)	Family labour (Man units)	Single Farm Payment (€)
Scotland, UK ^a	132	64	2.00	59,324
Aragon, Spain ^b	147	155	0.00	28,729

174 Source: ^a FAS (2012); ^b INE (2009)

175

176 2.2.2 Aragon

177 In Aragon, the fourth largest agricultural region in Spain, about one fourth of the land is
 178 dedicated to agricultural activities. As shown in Table 1, crop farms have 147 ha of
 179 arable land on average and grow cereal crops (wheat and barley), maize and alfalfa
 180 under irrigated and rain fed systems. Some of the farms also have land under almond,
 181 vineyard and olive production under a rain-fed system. The above mentioned crops
 182 account for 75% of the total cropland area of the region and the farms receive less than
 183 half of the single farm payments received by their counterparts in Scotland. There is
 184 also a considerable land area under grass on average.

185 Aragón is a semiarid region located in north-eastern Spain where the climate is
 186 Mediterranean with continental influence (i.e., mean annual temperatures about 7 °C to
 187 15 °C and mean annual precipitation from 300 to 800 mm). Agricultural management is
 188 mostly conventional based on intensive tillage, high fertilization rates (mineral and
 189 organic), frequent use of herbicides to control weeds and monocultures (Álvaro-
 190 Fuentes et al. 2011; Sánchez et al. 2016b).

191 **2.3 Farm level data**

192 The modelling work required detailed farm level data for each of the study regions. The
193 data was acquired from the Farm Accounting Survey (FAS) data for Scotland (FAS,
194 2012) and Aragon Census Data for Aragon, Spain (INE, 2009). The Scottish FAS data has
195 been found to represent farming activity well with respect to geographical distribution
196 and level of production (Scottish Government, 2013). For the Aragon region, INE (2009)
197 provides the most accurate and complete data for the specific inputs required for the
198 model. These two datasets provided farm level data for 135 crop farms in Scotland and
199 105 farms in Aragon. Data included information on farm characteristics including land
200 area under different crops, labour availability, farm subsidy payments, crop revenues
201 and costs of production. The crop farms were clustered into three types (large, medium
202 and small) based on different farm variables such as farm size and farm gross margins
203 using k-means clustering. Farm characteristics in each of the types are averaged and
204 used in the model as the “representative” arable farm for each type. The farm
205 characteristics relevant to the model include land use shares, average crop yields, crop
206 gross margins (derived from revenues collected minus costs of production) as well as
207 feed crops in Scottish farm groups.

208

209 **2.3.1 Scotland**

210 For Scotland, the cluster analysis was based on farm area, family labour and farm
211 payments and resulted in three representative farm types Crop Large, Crop Medium and
212 Crop Small with 67%, 26% and 7% of farms in the data allocated to the three clusters.
213 Farm characteristics of each of the types are shown in Table 2. There are four main

214 crops produced on the farm types, with differing average land allocations for the four
 215 crops in each of the farm types (Table 2).

216 **Table 2.** Farm characteristics (Scotland)

Farm type (% of farms in data in parentheses)	Grass- land (ha)	Rough grazing (ha)	Arable land (ha)				Family labour (Man Units)	Single Farm Payments (£)
			Wheat	Barley	Oats	Oilseed		
Crop Large (67%)	178.3	0	104.4	106.1	0	16	7.5	77,258
Crop Medium (26%)	86.3	6.9	50.3	130.7	7.4	23.1	2.7	80,350
Crop Small (7%)	46.6	5.1	17.6	61.9	3.6	4.2	1.5	34,023

217 Source: FAS (2012)

218

219 2.3.2 Aragon

220 In the Aragon region of Spain, crop farms were separated in three farm types based on
 221 agriculture area and number of farms. The farm types are (similar to Scottish farm
 222 types): Crop Large (11% of farms in the data), Crop Medium (45%) and Crop Small
 223 (44%). The characteristics of farms in each of the farm types, and the land allocated to
 224 crops on farms in the different types, are presented in Table 3.

225 **Table 3.** Farm characteristics (Aragon, Spain)

Farm type (% of farms in data in parentheses)	Grass- land (ha)	Rough grazing (ha)	Arable land (ha)											Single farm payments (€)
			Total	WR	WI	BR	BI	M	A	AM	V	O	F	
Crop Large (11%)	245.4	302.1	254.5	30.3	8.3	49.0	11.2	10.3	10.6	8.5	4.2	5.2	71.2	25,451
Crop Medium (45%)	209.8	246.3	172.4	20.5	5.6	33.2	7.6	7.0	7.2	5.8	2.8	3.5	48.2	17,245
Crop Small (44%)	10.9	10.2	12.8	1.5	0.4	2.5	0.6	0.5	0.5	0.4	0.2	0.3	3.6	1,278

226 Source: INE (2009)

227 Note: WR: Wheat (rainfed); WI: Wheat (irrigated); BR: Barley (rainfed); BI: Barley (irrigated); M: Maize;
 228 A: Alfalfa; AM: Almond; V: Vineyard; O: Olives; F: Fallow

229

230 **2.4 SOC management measures**

231 The suite of SOC management measures considered for this study is based on expert
232 opinion about the measures' feasibility in each case study region, and draws on
233 previous work on cost-effectiveness of SOC management and barriers for uptake in the
234 case study regions (McVittie et al. 2014; Sánchez et al. 2016a,b). Feasible SOC
235 management measures and crop combinations for each of the case study regions were
236 then selected based on the observed cropping activities in each region. The selected SOC
237 management measures can be characterized as follows, based on Wösten and Kuikman
238 (2014)² and Flynn et al. (2007), with specific reference to potential processes related to
239 carbon sequestration and GHG emission reduction in order to derive upper and lower
240 bounds for the effect these measures are expected to have on SOC (Table 4).

241 2.4.1 Cover crops (Scotland, Aragon)

242 This is the provision of a temporary vegetative cover between agricultural crops, which
243 is then ploughed into the soil. The vegetative cover can include legumes. These cover
244 crops very efficiently add carbon to soils (Poeplau and Don 2015) and non-legume
245 based cover crops may also extract plant-available nitrogen (N) unused by the
246 preceding crop, and thereby reducing leaching and therefore indirect nitrous oxide
247 (N₂O) emissions (Paustian et al. 2016). In the case of legume-based cover crops, the
248 amount of fertiliser N that needs to be added can be reduced (St Luce et al. 2016). Seed
249 mixes with legumes (e.g., clover) have higher cost and differ in fertiliser requirements,
250 but may result in greater SOC gains and yield effects than non-legume seed mixes,
251 although a recent meta-analysis does not support this finding (Poeplau and Don 2015).
252 Nevertheless, in water limited regions, cover crops may reduce yield (Blanco-Canqui et

² see Smith et al. (2007b) for a detailed description of agricultural SOC management measures.

253 al., 2015). For Scotland, as the opportunity cost (see McVittie et al., 2014) of switching
254 between winter and spring sown crops has not been considered in the model, only
255 spring barley and spring oats are considered to be affected under this scenario, which
256 comprise 60%-70% of the annual cereal hectare in Scotland.

257 2.4.2 Zero tillage (Scotland, Aragon)

258 Advances in weed control methods and farm machinery now allow many crops to be
259 grown without tillage (zero tillage or no till). In general, tillage promotes
260 decomposition, reducing soil carbon (C) stores and increasing emissions of GHGs
261 (Guardia et al. 2016), through increased aeration, crop residue incorporation into soil,
262 physical breakdown of residues, and disruption of aggregates protecting soil organic
263 matter. Therefore, zero tillage often results in SOC gains (Whitmore et al., 2015;
264 Paustian et al. 2016), although this may be the result of a change in the distribution of
265 the soil carbon through the profile (Powlson et al. 2014). Nevertheless, zero tillage
266 practices enhance the soil quality in terms of its microbial biomass and enzyme activity
267 (Melero et al. 2011, Mangalassery et al. 2015). The enhanced soil carbon in the top soil
268 and the increased soil quality is likely to have beneficial effects on production in the
269 long-term, although there is a risk of yield reduction in the short to medium term (Sun
270 et al., 2011).

271 2.4.3 Reduced tillage (Scotland)

272 Reduced tillage can take many forms including ridge tillage, shallow ploughing and
273 rotovation, or scarification of the soil surface. All cause less soil disturbance than
274 conventional deep tillage with a mouldboard plough. Reduced tillage decreases
275 decomposition and can enhance the soil quality (Melero et al. 2009), and increase the

276 SOC stock (Paustian et al. 2016). However, in the short to medium term, yields can be
277 reduced compared to conventional ploughing (Sun et al, 2011).

278 2.4.4 Residue management (Scotland, Aragon)

279 Residue incorporation, where stubble, straw or other crop debris is left on the field, and
280 then incorporated when the field is tilled, is used in some areas for water conservation,
281 but also enhances carbon returns to the soil, thereby encouraging carbon sequestration.
282 However, incorporation can increase N₂O emissions and therefore net benefits in terms
283 of climate mitigation may be highest when residues with high N content are removed.
284 The contribution of crop residues to soil organic matter differs per crop, and is
285 dependent on the carbon content (Justes et al. 2009). Crops with lower C:N ratios tend
286 to results in more of the N being mineralised and hence available to the following crop
287 (Justes et al. 2009). For the context of this paper, tillage operations are not assumed to
288 change and will thus remain conventional for this measure.

289 2.4.5 Fertilisation with animal manures (Aragon)

290 Incorporating animal manures to arable land is expected to encourage carbon
291 sequestration, because it increases organic carbon stores and enhances carbon return to
292 the soil. However, an increase in N₂O emissions can be associated with the manure
293 management undertaken (Freibauer et al. 2004). Manure management may imply large
294 infrastructure requirements in terms of improved storage and handling, and add extra
295 cost due to additional demand for labour and fuel (Smith et al. 2007a). In Spain, for
296 example, the low availability of manure on farms and the restrictive legislative
297 requirements for manure management, treatment and transportation (EU Nitrates
298 Directive 91/676/EEC) may limit its use by many farmers (Sánchez et al. 2016b).

299 2.4.6 Optimised fertiliser application (Aragon)

300 Being optimised and therefore more efficient in fertiliser application (at the right time
301 of the crop growth and under the most optimal weather and soil conditions) is
302 associated with lower fertiliser rates. Further, the optimised fertilisation stimulates the
303 plant growth, plant and root biomass and the microbial activity, having a direct impact
304 on SOC (López-Bellido et al. 2010). Particularly, N fertilisation should be managed by
305 site-specific assessment of soil N availability to be able to mitigate atmospheric CO₂
306 enrichment (Khan et al. 2007). In Mediterranean regions, N fertilisation was found to
307 have a long term effect on SOC dynamics depending to the management applied and the
308 soil water content (Morell et al. 2011a; Álvaro-Fuentes et al. 2012). Nevertheless,
309 optimising fertiliser application is unlikely to have a negative effect on SOC.

310 2.4.7 Crop rotation with legumes (Aragon)

311 Using crop rotations which include legumes increases soil carbon stores and requires
312 reduced fertiliser use, thereby reducing N₂O emissions. Inclusion of legumes in a cereal
313 crop rotation has a positive effect on the content and the quality of SOC. In Spain,
314 McVittie et al. (2014) report that this was not considered an appropriate practice in arid
315 areas with precipitation below 350 mm year⁻¹. Crop rotations have shown a positive
316 effect over time on SOC sequestration and content in rainfed Mediterranean due to C
317 additions as plant and root biomass, and due to better soil structure (López-Bellido et
318 al. 2010).

319

320 2.5 Effects of SOC measures

321 2.5.1 Effects on SOC content

322 The main policy interest in SOC management measures is to increase SOC stocks. While
 323 not relevant as a model input, SOC accumulation rates for the measures identified for
 324 the case study regions are listed in Table 4 to provide context for an appraisal of their
 325 effectiveness in achieving increases in SOC stocks. Reported values are based on expert
 326 knowledge guided by the literature quoted in section 2.4 and by papers that synthesise
 327 the effects of the measures on soil carbon (listed in Table 4). The 'best estimate' refers
 328 to typical rates whereas the lower and upper bound values (Min and Max) reflect the
 329 uncertainty regarding the assumptions behind SOC accumulation estimates.

330

331 **Table 4.** SOC accumulation rates for measures in kgC ha⁻¹ yr⁻¹

SOC measures		Best estimate	Lower bound	Upper bound	Relevant synthesis papers
Cover crops (legume)		400	0	800	Smith et al (2008); Lal and Bruce 1999; Steenwerth and Belina 2008; Nieto et al. 2013; Ogle et al, 2005; Poeplau and Don 2015
Cover crops (non-legume)		200	0	400	
Zero tillage		0	-100	100	Smith et al (1997, 1998); Freibauer et al (2004); West and Post (2002); Sun et al. (2011); Troccoli et al (2015); Whitmore et al (2015)
Reduced tillage		0	-100	100	Ball et al. (1994); Arrouays et al (2002); Bhogal et al (2007); Sun et al. (2011); Powlson et al 2012
Residue management	Years 0-20	400	0	800	Powlson et al (2008); Freibauer et al (2004); Powlson et al (2012); Troccoli et al. (2015) Pituello et al. (2015)
	Years 21-25	300	0	600	
Fertilisation with animal manures		200	0	400	Paustian et al. 1997; Smith et al. 1997; Follet 2001; Smith et al. 2008; Freibauer et al. 2004; Oberholzer et al. (2014); Whitmore et al (2015)
Optimised fertiliser application		0	0	100	Lal and Bruce 1999; Follet 2001; Snyder et al. 2009
Crop rotations (with legumes)		400	0	800	Lal and Bruce 1999; Follet 2001; West and Post 2002; Lal 2004

332 2.5.2 Effects on yield, nutrient availability and elements of variable costs

333 2.5.2.1 Yield

334 Table 5 reports average yield for crops in the two case study regions. The values define
335 yield in the baseline scenario (no SOC management measures) of the model. Yield
336 changes as result of SOC management measures are then included in the model relative
337 to these baseline yield values.

338

339 **Table 5.** Baseline yields for crops in Scotland (UK) and Aragon (Spain)

Crops	Average yields (t/ha)	
	Scotland ^a	Aragon ^b
Winter wheat	8.5	-
Spring barley	6.5	-
Spring oats	5.7	-
Wheat (rainfed)	-	2
Wheat (irrigated)	-	4
Barley (rainfed)	-	2.3
Barley (irrigated)	-	3.7
Maize(irrigated)	-	9.5
Alfalfa (irrigated)	-	15.2
Almond (rainfed)	-	0.5
Vineyard (rainfed)	-	3.3
Olives (rainfed)	-	0.8

340 Source: ^aSAC Farm Management Handbook 2012/13 (SAC 2012); ^b Spanish Agricultural Census
341 1999/2011

342

343 Table 6 reports the plausible range of changes in crop yields for the SOC management
344 measures considered for the case study regions. Changes in yield show a similar pattern
345 for the SOC management measures common to both case study regions. However, cover
346 crop effects are more pronounced in Aragon (see Gabriel and Quemada 2011; Blanco-
347 Canqui et al 2015) and tillage is assumed to have a greater effect on yield after the initial
348 years (see Table 6 for references); however there is an increased risk of the yield being
349 reduced in wet seasons (Soane et al. 2012).

350 **Table 6.** Percentage (%) change in yield under different SOC measures in t C ha⁻¹

SOC measures	Years	Scotland			Aragon			References
		Mean	Min	Max	Mean	Min	Max	
Cover crops (legume)		+5	+0	+20	+10	-10	+30	Gabriel and Quemada (2011); Li et al. (2015); Blanco-Canqui et al. (2015)
Cover crops (non-legume)		+0	-5	+10	+5	-5	+10	Gabriel and Quemada (2011); Li et al. (2015); Blanco-Canqui et al. (2015)
Zero tillage ^a	0-9	-5	-20	+5	-5	-20	+5	Cantero-Martínez et al (2003); Sun et al. (2011); Morell et al. (2011b); Soane et al. (2012); Mangalassery et al (2015); Troccoli et al (2015)
	10-25	+0	-10	+10	+40	+20	+50	Sun et al. (2011); Soane et al. (2012); Troccoli et al. (2015)
Reduced tillage	0-9	-2	-10	+10	-	-	-	Cantero-Martínez et al (2003); Sun et al. (2011); Morell et al. (2011b); Troccoli et al. (2015); Townsend et al. (2016a)
	10-25	+0	-10	+10	-	-	-	Sun et al. (2011); Troccoli et al. (2015); Townsend et al. (2016a)
Residue management		+0	-10	+10	+0	-10	+10	Pituello et al. (2015)
Fertilisation with animal manure		-	-	-	+25	+10	+40	Lehtinen et al. (2014)
Optimised fertiliser application		-	-	-	+3	-30	+35	Brisson et al (2010)
Crop rotations (with legumes)		-	-	-	+30	+20	+50	Preissel et al. (2015)

351 Note ^a In Aragon expert opinion identified that the actual implementation of reduced till is very similar in
 352 terms of effects and costs is very similar to zero till, and therefore only zero-till was implemented in the
 353 model.

354

355 *2.5.2.2 Nutrient availability*

356 SOC management measures may allow substitution of organic and/or inorganic
 357 fertiliser application due to improved nutrient availability. For example, Carvalho et al.
 358 (2005) found that for an increase in SOC content from 1% to 2%, resulted in up to 62 kg
 359 N ha⁻¹ becoming available to the crop. However, for some of the investigated SOC

360 management measures such as zero and reduced tillage and residue management, no
361 substitution of fertiliser through increased availability of nutrients is possible in the
362 years following adoption due to immobilisation (Luxhøi et al. 2008); in fact, nutrient
363 availability may temporarily decrease. Together with optimised fertiliser application in
364 Aragon, fertiliser replacement potential is greatest for N fixing cover crops (legumes).
365 However, these measures also have the greatest variation in N substitution possibilities.
366 For the following years, replacement potential is greatest for N fixing cover crops (e.g.,
367 legumes). However, cover crops also have the greatest variation in N substitution
368 possibilities.

369 Generally, effects on nutrient availability are likely to affect N, P and K availability. It
370 would be interesting to consider impacts of SOC management measures on N, P and K
371 separately. However, since reliable data from field experiments is lacking, this would
372 require a series of assumptions that are not necessarily productive to generate more
373 accurate or reliable model outcomes. Given the above, the assumed effects on nutrient
374 availability as reported in Table 7 refer to crop specific N requirements and
375 corresponding ratios of P and K requirements. Regarding SOC measures that are only
376 considered for Aragon, Spain, mineral fertiliser can fully be replaced by organic
377 fertiliser (for maize, some mineral fertiliser would need to be added to the organic
378 application). Assumed reductions in fertiliser requirements of 23% from the baseline
379 average optimised fertiliser applications are based on Van Alphen and Stoorvogel
380 (2000).

381 An average price of € 0.8 kg⁻¹ fertiliser is applied to derive an estimate of the
382 difference that fertiliser substitution would have on farm gross margins. The value of €
383 0.8 kg⁻¹ fertiliser results from recommended fertiliser requirements divided by the

384 variable fertiliser costs per ha listed in the SAC Farm Management Handbook 2013/14
 385 (SAC 2013) for the 'mean' yield scenarios. Of course, there is a possibility that a certain
 386 level of replacement due to SOC management measures could result in less operations
 387 necessary, but thresholds for this are likely to vary across crop types and farm types
 388 and are difficult to establish and were therefore not considered.

389

390 **Table 7.** Fertiliser substitution effects (kg ha⁻¹ fertiliser) for SOC measures

SOC measures	Year	Scotland			Aragon		
		Mean	Min	Max	Mean	Min	Max
Cover crops (legume)		30	50	10	30	50	10
Cover crops (non-legume)		+0	15	-5	+0	15	-5
Zero tillage	0-5	-10	5	-15	-5	5	-15
	6-25	+0	40	-10	13	40	-10
Reduced tillage	0-5	+0	5	-5	-	-	-
	6-25	+0	20	-5	-	-	-
Residue management	0-5	-10	5	-15	-10	5	-15
	6-25	5	40	-10	15	40	-10
Fertilisation with animal manures		-	-	-	+0	+0	+0
Optimised fertiliser application	0-5	-	-	-	+0	+0	+0
	6-25	-	-	-	28	62	-6
Crop rotations (with legumes)	0-5	-	-	-	+0	+0	+0
	6-25	-	-	-	62	74	25

391 Note: Negative values for fertiliser substitution effects reflect an increase in fertiliser needs, which in turn
 392 implies a decrease in farm gross margins entering the farm level model.

393

394 2.5.2.3 *Weed and pest control*

395 With respect to weed control and pesticide/fungicide use, changes were defined as
 396 percentage changes of the different SOC management measures from the mean
 397 expenditure on weed control as reported in the SAC Farm Management Handbook
 398 2013/14 (SAC 2013). Changes in costs associated with weed and pest control, and
 399 implied absolute changes in costs, are assumed to be similar for Scotland and the
 400 Aragon case study (Table 8).

401

402 **Table 8.** Percentage (%) changes in weed control and spraying costs for SOC
 403 management measures

SOC measures	Scotland			Aragon		
	Mean	Min	Max	Mean	Min	Max
Cover crops (legume and non-legume)	+0	-20	20	+0	-20	20
Zero tillage	30	+0	60	25	+0	50
Reduced tillage	20	+0	40	-	-	-
Residue management	10	+0	20	10	+0	20
Fertilisation with animal manures	-	-	-	+0	+0	+0
Optimised fertiliser application	-	-	-	+0	+0	+0
Crop rotations (with legumes)	-	-	-	+0	+0	+0

404 Note: Scotland: Changes relative to baseline as reported in SAC (2013): winter wheat €160 ha⁻¹; winter
 405 barley €110 ha⁻¹; spring barley €62.5 ha⁻¹; winter oats €75 ha⁻¹; spring oats €65 ha⁻¹; Spain: Note:
 406 Changes relative to baseline: wheat (rainfed) €14 ha⁻¹; wheat (irrigated) €26 ha⁻¹; barely (rainfed) €20
 407 ha⁻¹; barley (irrigated) €32 ha⁻¹; maize (irrigated) €78 ha⁻¹; alfalfa (irrigated) €36 ha⁻¹; almond (rainfed)
 408 €50 ha⁻¹; vineyard (rainfed) €138 ha⁻¹; olives (rainfed) €19 ha⁻¹

409

410 2.5.2.4 Cost of field operations

411 SOC management measures can result in changes in costs for field operations (see e.g.
 412 Morris et al. 2010), that is, use of machinery and associated time and fuel costs for
 413 ploughing, tillage, seeding and, in case of residue management, bailing of straw. The
 414 values used in the farm level models are reported in Table 9, developed using expert
 415 judgment and for the Scottish case study region baseline figures for field operations
 416 from SAC (2013). Cover crops are assumed to be associated with a slight increase
 417 related to the need for seeding and killing of the cover crop (e.g., Pratt et al. 2014). Zero
 418 and reduced tillage are assumed to result in no costs for ploughing and a slight decrease
 419 is assumed for tillage operations (Morris et al. 2010) and residue management (no need
 420 for bailing of straw). In the case of optimised fertiliser application, the cost refers to the
 421 cost of performing soil analysis.

422

423

424 **Table 9.** Changes in field operation costs (€ ha⁻¹) for SOC management measures
 425 (Scotland)

SOC measures	Scotland			Aragon		
	Mean	Min	Max	Mean	Min	Max
Cover crops (legume and non-legume)	26.3	8.8	43.8	30	10	50
Zero tillage	-87.5	-105	-70	-10	0	-20
Reduced tillage	-70	-87.5	-52.5	-	-	-
Residue management	-17.5	-35	-8.8	-20	-40	-10
Fertilisation with animal manures	-	-	-	140	75	200
Optimised fertiliser application	-	-	-	6	3	10
Crop rotations (with legumes)	-	-	-	0	0	0

426

427 *2.5.2.5 Seed costs (cover crops)*

428 Seed costs for establishing a cover crop vary widely depending on the type of cover crop
 429 used. The choice of cover crop (legume or non-legume) can affect the nutrient
 430 availability effect. We assumed seed costs to be €70 ha⁻¹ (Scotland, Aragon) on average
 431 if they entail legumes, and €30 ha⁻¹ (Scotland) and €40 ha⁻¹ (Aragon) on average if they
 432 do not. Seed costs may be as low as €17.5 ha⁻¹ for some rye grass varieties but may
 433 exceed €100 ha⁻¹ for some legumes. Consequently, seed costs for both Scotland and
 434 Aragon vary between a minimum of €20 ha⁻¹ and a maximum of € 120 ha⁻¹.

435

436 *2.5.2.6 Forgone value of straw (residue management)*

437 As a final cost element specifically related to residue management is the forgone
 438 production value of straw. How straw is used after it is being bailed and hauled depends
 439 on local demand for straw within the same farm or as a commodity sold to other users
 440 (e.g. livestock farms or biomass plants). We assume that changes in straw production
 441 are proportional to yield change. Table 10 reports baseline straw yields, which are
 442 multiplied by the expected yield change (equal to one if there is no change in yield) and
 443 the value of straw in € t⁻¹ to derive the annual value of the forgone production of straw

444 used in the farm models. Values of straw are assumed to be €35 t⁻¹ on average for both
 445 Scotland and Aragon, and vary from €13.1 t⁻¹ to €56.9 t⁻¹ for Scotland, and from €25 t⁻¹
 446 to €45 t⁻¹ for Aragon.

447

448 **Table 10.** Baseline straw yields (t ha⁻¹)

Crops	Scotland	Aragon
Winter wheat	4.2	-
Spring barley	2.9	-
Spring oats	3	-
Wheat (rainfed)	-	4.9
Wheat (irrigated)	-	6.6
Barley (rainfed)	-	5.8
Barley (irrigated)	-	6.2

449 Source Scotland: SAC Farm Management Handbook 2013/14 (SAC 2013); Source Spain: Moragues et al.
 450 2006; Urbano 2002; Francia et al. 2006; Pordesimo et al. 2004

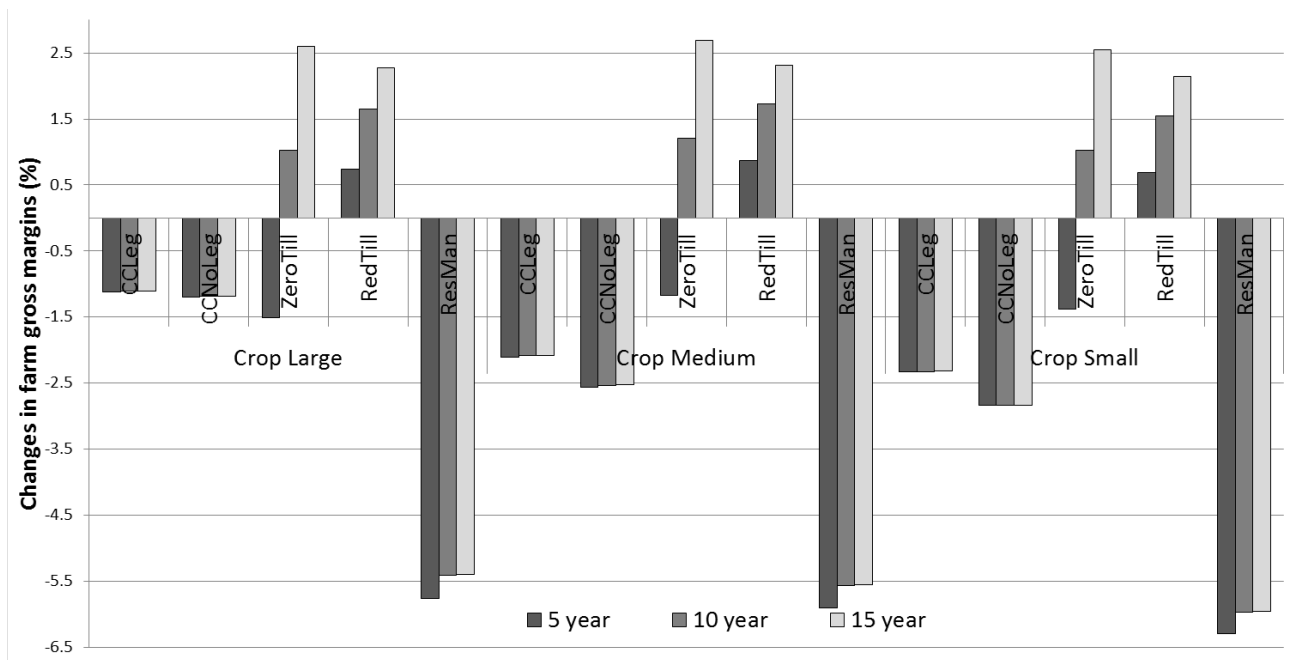
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452 **3 Results**

453 **3.1 Scotland**

454 Figure 3 shows the changes in farm gross margins for the three farm types investigated
 455 for Scotland and the SOC management measures compared to the baseline. All crop
 456 farm types benefit financially from both reduced and zero tillage measures in the long
 457 term (see Figure 3). Crop yields decrease by 5% (reduced tillage) and 2% (zero tillage)
 458 for the first 5 years, and increase by 5% in subsequent years. The main benefit arises
 459 from savings in input costs associated with tillage. Residue management results in the
 460 largest negative effect on farm gross margins (up to -6%) in all three farm types. Crop
 461 yields remain unchanged under this measure, but a substantial loss in straw revenues
 462 reduces farm gross margins. The cover crop measures have a small but negative effect
 463 (< -3%) across all farm types.

464



465

466 **Figure 3.** Percentage change in gross margins under different SOC options compared to the
 467 baseline for Scottish farm groups: CCLeg = cover crop with legume; CCNoLeg = cover crop
 468 without legumes; ZeroTill = zero tillage; RedTill = reduced tillage; ResMan = residue
 469 management

470 Results of the sensitivity analysis (which is run for the four cases: $Y_{\max}C_{\max}$, $Y_{\max}C_{\min}$,
 471 $Y_{\min}C_{\max}$ and $Y_{\min}C_{\min}$) for the Scottish context are presented in Figure 4 (see also
 472 supplementary material Table S1). Assumptions on crop yields have a greater effect on
 473 farm gross margins than variation in input costs. An exception is residue management,
 474 where farm gross margins are equally sensitive to assumptions regarding yield effects
 475 and changes in input costs, which are in particular associated with the forgone value of
 476 straw. Residue management only achieves a positive effect for upper bound yield effects
 477 and lower bound assumptions on input costs ($Y_{\max}C_{\min}$). Additionally, farm gross
 478 margins for residue management can decrease considerably by up to 30%.

479 There are only small differences between the two cover crop measures (legume and
 480 non-legume) across all four cases. Legume cover crops have greater positive yield
 481 effects, especially at the upper bound (Y_{\max}). However, seed costs can be considerably
 482 higher for cover crops using legumes. This is reflected in lower farm gross margins

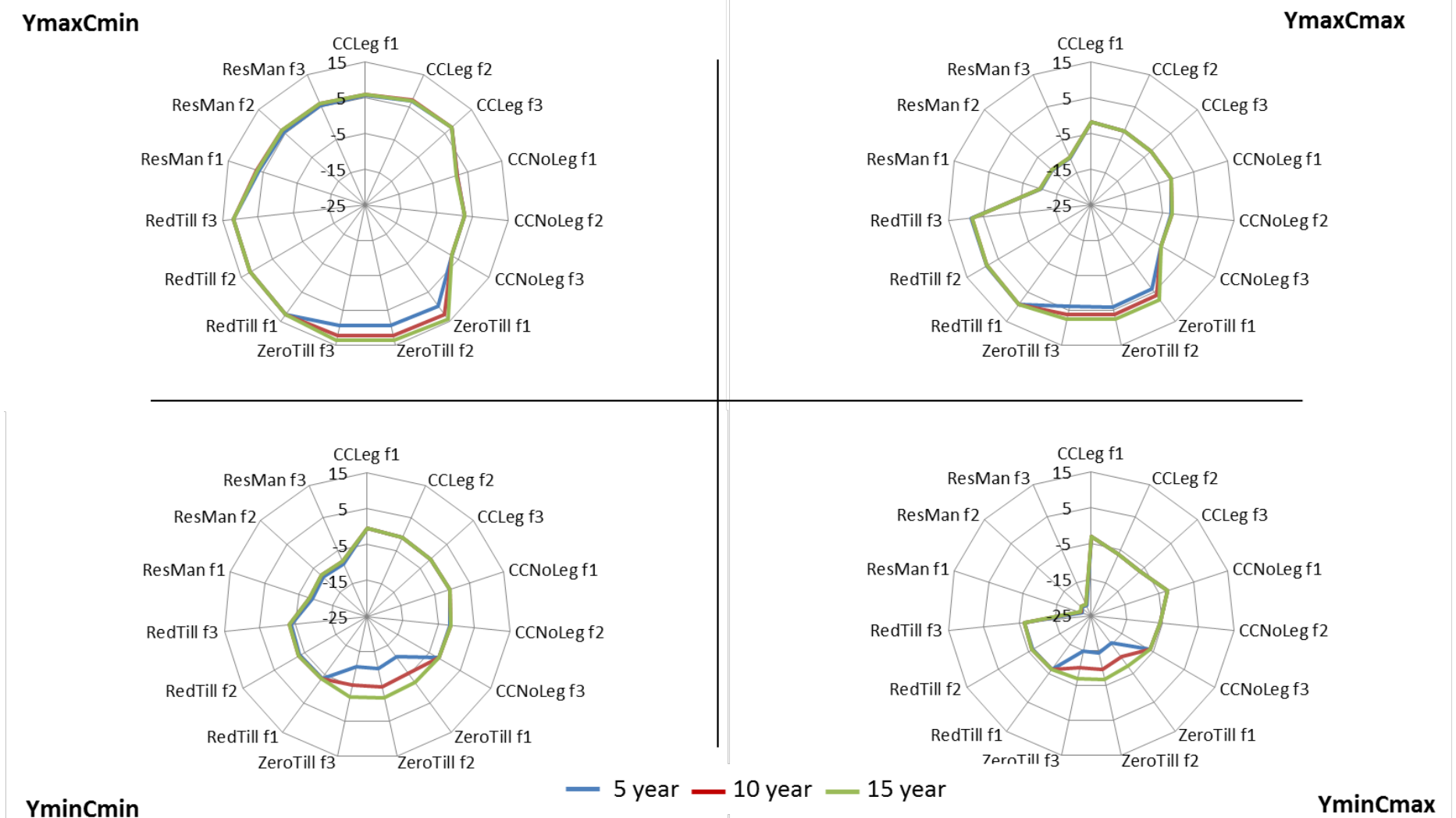
483 compared to non-legume cover crops in the $Y_{\min}C_{\max}$ case. The cover crop SOC
484 management measures are overall quite robust to changes in assumptions; i.e., effects
485 on farm gross margins are in the range of -5% to +5% across the four sensitivity
486 analysis cases. However, cover crop measures lack the potential for substantial positive
487 effects that are particularly apparent for zero and reduced tillage measures in the
488 $Y_{\max}C_{\min}$ case (up to 14% increase after 5 years).

489 Reduced tillage performs always better or at least equally well as zero tillage across all
490 time periods, and yield effects are key to both tillage measures to arrive at positive
491 effects on farm gross margins. Additionally, zero tillage appears to be particularly
492 sensitive to yield effects in earlier years. Figure 4 also shows that the patterns of
493 sensitivity found do not differ much across farm types.

494

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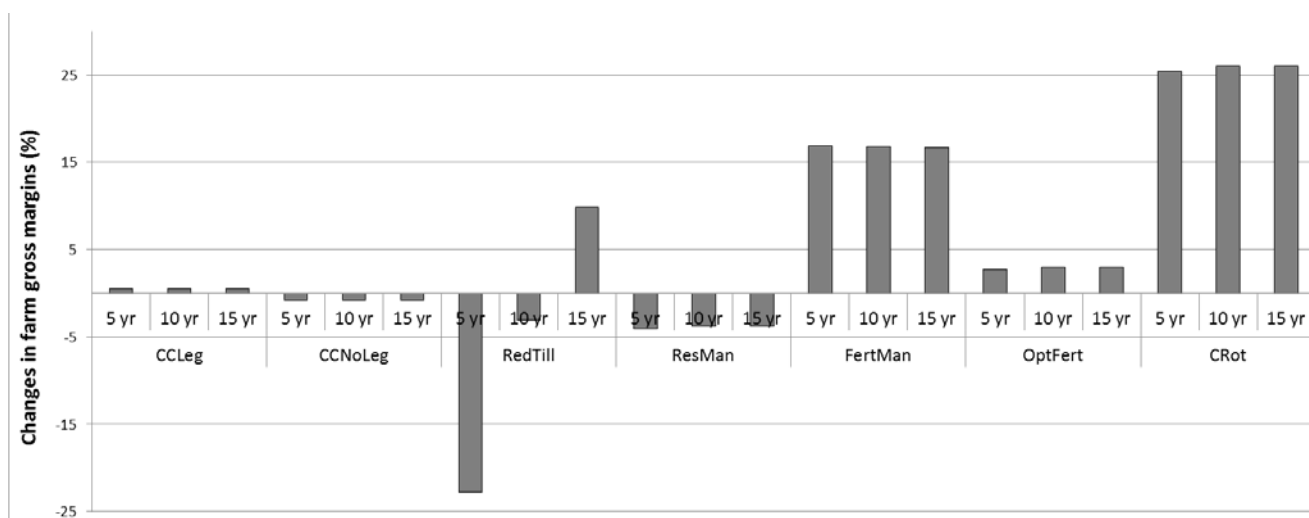
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Figure 4. Percentage changes in farm gross margins compared to the baseline under sensitivity analysis of crop yield and crop gross margins: CCleg = cover crop with legume; CCNoLeg = cover crop out legumes; ZeroTill = zero tillage; RedTill = reduced tillage; ResMan = residue management; f1 = large sized crop farm group; f2 = medium sized crop farm group and f3 = small sized crop farm group

501 **3.2 Aragon**

502 Unlike Scottish farms in the study, relative farm gross margin effects of Aragon farms
 503 lack variability between the three farm types for the SOC management scenarios. The
 504 main reasons are the interaction of crop and livestock systems on Scottish farms, and
 505 the availability of additional farm-type specific input parameters, for example regarding
 506 family labour, for Scottish farms. Because differences in relative farm gross margin
 507 effects between farm types are negligible for Aragon, the results displayed in Figure 5
 508 and in the following sensitivity analysis (Figure 6) show average relative gross margin
 509 effects across all farm types.

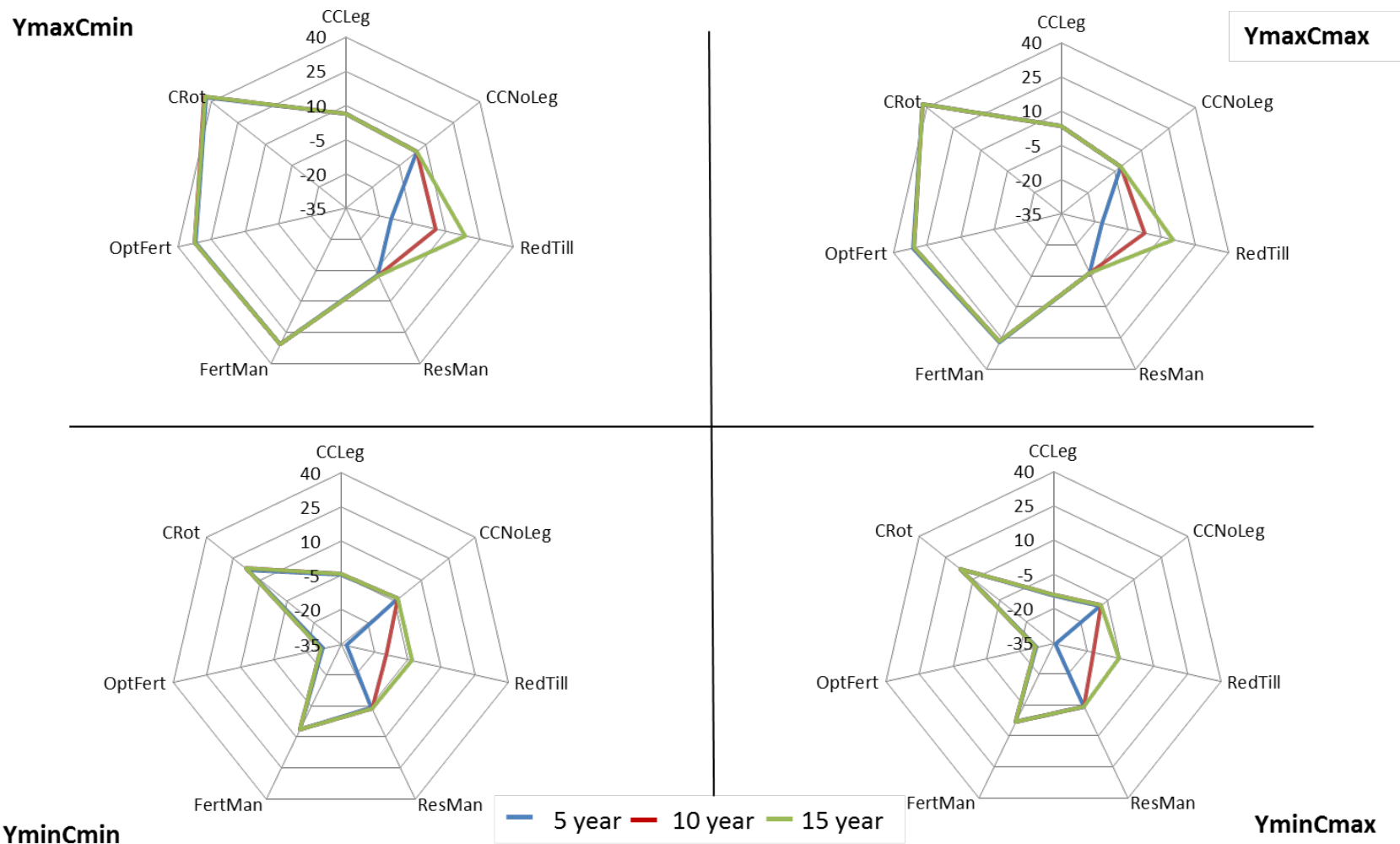


510
 511 **Figure 5.** Percentage changes in farm gross margins under different SOC options compared to
 512 the baseline for on farm in Aragon region of Spain: CCleg = cover crop with legume; CCNoLeg =
 513 cover crop with no legume; ZeroTill = zero tillage; RedTill = reduced tillage; ResMan = residue
 514 management; FertMan = fertilisation with animal manure; OptFert = optimal use of fertiliser
 515 and CRot = crop rotation

516 All of the SOC measures projected to increase yields of the main crops except for tillage
 517 management in earlier time periods and residue management. Tillage management is
 518 assumed to result in a slight decrease in yield (5%) in the first 10 years, but yield
 519 increases substantially (40% relative to business as usual) after that. This is reflected in
 520 a 22% and 5% reduction in farm gross margins after 5 and 10 years, but an increase in
 521 farm gross margins of 10% after 15 years (Figure 5). There is no change in yields

522 expected for the residue management measure in the baseline scenario, but due to
523 forgone revenue from straw, farm gross margins decrease by up to 4%. There is no
524 substantial change in farm gross margins under both of the cover crop options. The
525 increase in crop yields and increases in input costs almost off-set each other for these
526 management measures. Fertiliser management and crop rotation result in increased
527 farm gross margins, which can be largely explained by crop yields being assumed to
528 increase by up to 30%.

529 Similar to the Scottish case study, the sensitivity analysis for the Aragon case study
530 shows that effects on farm gross margins are more sensitive to changes in crop yields
531 than to changes in input costs (Figure 6; see also supplementary material Table S2). SOC
532 management measures have a positive effect for the case of upper bound crop yields
533 ($Y_{\max}C_{\max}$ and $Y_{\max}C_{\min}$) except for cover crops (non-legume) and residue management,
534 which does not show a positive effect in all four sensitivity analysis cases. Tillage
535 management measures initially (by 5 years) show a negative effect, which is reversed in
536 later years. The greatest positive effect on farm gross margins is found for crop rotation
537 management measures when yields are at the maximum and input costs are at the
538 minimum ($Y_{\max}C_{\min}$). Fertilisation with animal manure and crop rotation (with
539 legumes) are relatively robust in their positive effect across all four combinations of
540 upper and lower bound estimates for crop yield effects and input costs. This differs
541 from the pattern found for optimised fertiliser application. In the cases of upper bound
542 crop yields (Y_{\max}), it is only second to the crop rotations measure in its positive effect on
543 farm gross margins. However, optimised fertiliser application shows the largest
544 negative effect on farm gross margins by 15 years (minus 25%) if yield effects are
545 assumed to be at the lower bound (Y_{\min}).



546

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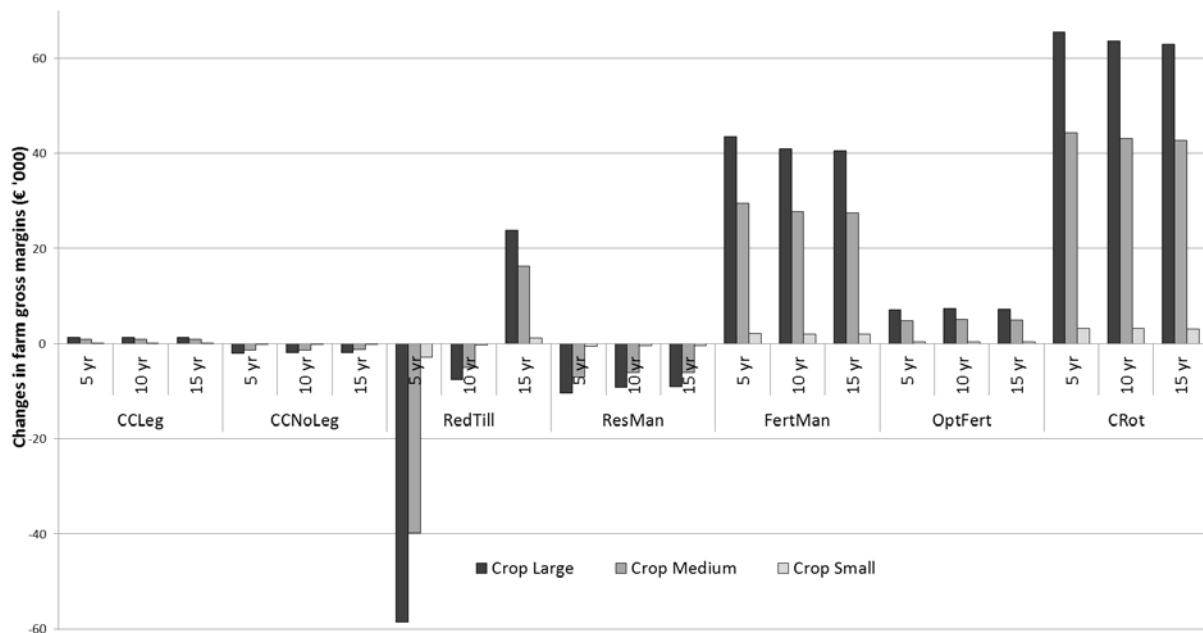
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Figure 6. Percentage changes in farm gross margin compared to the baseline under sensitivity analysis of crop yield and crop gross margins on farms in Aragon region of Spain margins CCLeg = cover crop with legumes; CCNoLeg = cover crop without legumes; ZeroTill = zero tillage; RedTill = reduced tillage; ResMan = residue management; FertMan = fertilisation with animal manure; OptFert = optimal use of fertiliser and CRot = crop rotation

551 Although, as stated earlier, the difference in gross margin effects is negligible across all
 552 three farm types for Aragon, farm gross margin effects differ in absolute terms (Figure
 553 7). The extent of the effect very much represents the size of the farm: the larger the size
 554 of the farm, the greater the absolute change in farm gross margins.

555



556

557 **Figure 7.** Absolute changes in farm gross margins (GM) compared to the baseline GM for farm
 558 groups in Aragon region of Spain: CCLeg = cover crop with legume; CCNoLeg = cover crop
 559 without legumes; ZeroTill = zero tillage; RedTill = reduced tillage; ResMan = residue
 560 management; FertMan = fertilisation with animal manure; OptFert = optimal use of fertiliser
 561 and CRot = crop rotation

562

563 4. Discussion

564 Tillage management was found to have a positive effect on farm gross margins in both
 565 case study regions in later years. As pointed out by Townsend et al. (2016b) in a study
 566 investigating farm level impacts of tillage management in England using a bio-economic
 567 optimisation model, actual financial benefits (i.e. farm net margins) of reducing tillage
 568 intensity can be higher than gross margin effects suggest if benefits of, for example, in
 569 terms of reduced labour costs or machinery use are taken into account. Townsend et al.

570 (2016b) find that the magnitude of yield decrease that would be required to off-set any
571 benefits of tillage management measures in terms of gross margins tends to increase
572 with decreasing tillage intensity; however, the benefits of tillage are affected by crop
573 and rotation (Townsend et al. 2016a) and the importance of soil water retention
574 (Troccoli et al. 2015). For the baseline scenario, we also find that zero tillage ultimately
575 results in greater gross margin gains compared to reduced tillage. However, the
576 comparative advantage disappears if input costs savings are limited, for example
577 because of an increased need for weed and pest control.

578 Additionally, in both Scotland and Aragon, zero tillage shows positive effects only in
579 later years (due to a delay in yield effects), whereas initially farm gross margins
580 decrease. This can have important consequences for uptake, because the lagged effect
581 can contribute to perceived uncertainty regarding impacts on farm productivity, which
582 Prager and Posthumus (2010) regard as a barrier to uptake. Consequently, risk averse
583 farmers aiming to adopt SOC measures would likely opt for alternative management
584 measures or retain their current management.

585 Therefore, if zero tillage was to be promoted as a SOC management measure, the factors
586 determining yield in early years of implementation need to be better understood to
587 increase the probability of less adverse yield effects in the first years, thus reducing
588 uncertainty.

589 The results show that there is limited variability in effects of SOC measures between
590 different farm types. All of the crop farms are assumed to be on similar soil type and
591 have very similar management measures. The only major difference between the farms
592 is size of farm and scale of production. Our assumption behind the changes in crop
593 yields and costs of production is generalised across all farm types. A more detailed set of

594 assumptions for each farm type would most probably bring out some variability in the
595 effects of the SOC management measures on different farm types. This could include
596 differentiating the effect of the soil management on SOC and yields by farm type and soil
597 type. This may be achieved by using a dynamic and deterministic model of the soil
598 carbon and nitrogen dynamics (e.g. Taghizadeh-Toosi & Olesen, 2016; Holzworth et al.,
599 2014; Parton and Rasmussen, 1994).

600 The results of the sensitivity analysis demonstrate the relative robustness of SOC
601 management measures from a financial perspective at the farm level. The information
602 derived from this study should not be used as a predictive tool for policy makers and
603 farmers; rather, we seek to demonstrate important considerations that affect the uptake
604 and profitability of SOC management measures. While these considerations need to be
605 carefully evaluated by decision makers on a case-to-case basis, the results presented in
606 this paper help to identify SOC measures that are most robust to changes in underlying
607 assumptions regarding yield and nutrient availability effects.

608 Gross margin effects of SOC management measures on farm gross margins are found to
609 be more sensitive to a change in crop yields than to changes in input costs. Therefore, it
610 may be concluded that effects of SOC management measures on fertiliser requirements
611 (and associated changes in cost) are not making a large difference to farm gross
612 margins. However, this could change if the prices of fertiliser/other inputs change
613 relative to crop prices compared to the baseline. It may also be important to take a
614 careful look at fertilisation effects through experiments and modelling studies (e.g. for
615 cover crops, Li et al., 2015; Autret et al., 2016; and inorganic fertiliser, Riley 2016;
616 Godde et al 2016), thereby better understanding the biophysical relationships that
617 underpin them.

618 The results of modelling suggest utilising manure and crop rotations would be financial
619 beneficial to the farmers; however, fertilisation with manure is less widely adopted in
620 Aragon than crop rotations (Sánchez et al. 2016b). One likely reason for the difference
621 in uptake is that crop rotations (with legumes) is the only SOC management measure
622 investigated that currently receives direct subsidies under the Common Agricultural
623 Policy (CAP) in Aragon. Also, the modelling framework assumes that the farmers are
624 profit maximisers, however for a variety of reasons (Moran et al., 2013; Buri et al,
625 2016), farmers may not behave rationally. Especially in relation to soil management,
626 farmers' behaviour may also be motivated by other factors such as perceived
627 workability of the soil, soil health for future generations or short-term financial benefits.
628 The salience of such motivations for improved soil management is, however, unclear
629 and remains an area that needs further investigation. In addition, the model assumes all
630 farms within a farm type are the same; whereas in reality they will differ in their
631 structure and their financial and biophysical characteristics (Moran et al., 2013).

632 The robustness of effects on farm gross margins differs across SOC management
633 measures in the case study regions. This finding points to a need for a more detailed
634 understanding of local environmental and farm management factors that affect yields
635 and input costs. In the absence of such information being available to farmers, measures
636 such as cover crops in Scotland and Aragon, for example, may be attractive to risk
637 averse farmers even without additional financial incentives that could serve as an
638 insurance against reduced productivity (Deeks et al. 2008). Despite lower projected
639 positive effects on gross margins compared to alternative SOC management measures,
640 the effects of the cover crop measure on farm gross margins is relatively robust to
641 variation in effects on yield and input costs. Given that cover crops can have a
642 considerable impact on increasing SOC stocks, ways to encourage further uptake should

643 be developed. Fertilisation with animal manures and crop rotation (with legumes) are
644 found to have robust effects on gross margins in the Aragon case study. Both measures
645 are reported to have considerable potential to increase SOC stocks, and positive effects
646 on farm gross margins are found to be relatively robust across all four combinations of
647 upper and lower bound estimates for crop yield effects and input costs. This is in
648 contrast with optimised fertiliser application, which can yield considerable positive
649 estimates, but which is also found to decrease gross margins if yield effects are at their
650 lower bound, therefore making it relatively unattractive to risk averse farmers.

651 Using plausible ranges of key parameters regarding the effects on nutrient availability,
652 yield effects, pest control and farming operations derived from expert knowledge and
653 guided by available literature may be considered second-best to a complex bio-
654 economic model. However, rather than aiming for a detailed understanding of bio-
655 physical processes underpinning crop production or environmental impacts (e.g.,
656 Reckling et al. 2016), this paper investigates the potential *range of variation* in gross
657 margins associated with changes in SOC management for representative farms in a
658 study region. In this respect, using plausible ranges rather than modelled estimates for
659 changes in inputs and yield is advantageous since it allows greater control over key
660 determinants of farm gross margins; and circumvents problems arising from
661 uncertainty associated with defining bio-physical parameters at the farm scale for a
662 'representative farm' in a particular study region.

663 Although based on farming system analysis, the farm level model, ScotFarm only
664 includes changes in yield and input costs of production under all SOC measures. The
665 model then adjusts the farming activities based on those changes. SOC management
666 measures may not only affect yields and input costs, for example through fertilisation

667 effects, but also other aspects that affect farm level economics that were not covered in
668 this study. This includes effects on timing and seasonal of labour resource availability
669 and capital costs associated with switching to a different management. Anecdotal
670 evidence also points to impacts of SOC management measures on, for example, soil
671 structure and workability.

672 The results do not consider interaction effects between SOC measures, which could
673 affect their effect on yield and input costs considered in the model. For example, cover
674 crops may be combined with a changed tillage system and crop rotation (Gillier et al.
675 2015). Additionally, because we consider only variable cost, potential synergies related
676 to, for example, machinery use across various SOC management measures are not
677 considered.

678 It is assumed that a farmer can easily implement the management measures and does
679 not face barriers regarding access to capital and technology (machinery) required for
680 their implementation. This assumption was necessary due to the widely unknown
681 reference conditions in Scottish arable farms. McVittie et al. (2014) report findings from
682 a series of workshops with farm consultants on barriers for uptake of the four
683 management measures included in this study. Access to capital or machinery was not
684 identified as a barrier. Sánchez et al. (2016b) identify barriers for uptake of agricultural
685 practices, including measures that enhance SOC, based on an econometric analysis of
686 farm surveys in Aragon, Spain. Financial incentives and access to technical advice were
687 amongst the main factors defining farmers' barriers to implementation.

688 Our results demonstrate the sensitivity of financial gains of SOC management on the
689 farm level to assumptions regarding yield effects and input costs. To some degree, these
690 can be influenced at the farm level, for example through careful weed and pest

691 management following the switch to zero or reduced tillage. Nevertheless, from the
692 farmers' perspective, the actual financial impacts of implementing the SOC management
693 measures is unknown and at least partially dependent on external factors such as
694 weather conditions and market prices. This makes investment into changes in
695 management measures a risky choice. An extension of the model should therefore
696 incorporate an element of risk, for example through the development of probabilistic
697 outcomes for yield effects and costs over the years. This aspect is of interest, because
698 SOC management measures may contribute to yield reliability (that is, to reducing
699 variability in yield) over time, for example by improving the water holding capacity of
700 the soil (Zibilske and Bradford 2007; Powlson et al. 2014) and therefore the capacity to
701 overcome longer periods of drought. This may become increasingly important in the
702 context of climate change adaptation (Williams et al. 2016).

703 In order to evaluate the SOC management measures from a broader policy perspective,
704 it is important to consider how they perform in terms of changes SOC stocks, especially
705 in areas with low SOC stocks and a high risk of further decline in SOC under the current
706 management regime. Further research should consider linking farm level models with a
707 more detailed SOC model to allow assessments of cost-effectiveness of management
708 measures, and the development of regional models that optimise the allocation of
709 management measures according to economic and soil management (SOC stocks)
710 objectives.

711 Further, impacts of SOC management measures on greenhouse gas emissions and other
712 co-effects including improvements in water quality for example related to nitrogen
713 leaching (Reckling et al. 2016), or biodiversity, should be assessed (Glenk and Colombo
714 2011). These benefits to the public can play an important role in justifying government

715 support for improved SOC management, for example in the form of financial incentives
716 for farmers that have previously been found to be a major factor in decisions to adopt
717 SOC management measures.

718

719 **5. Conclusions**

720 Knowledge on private financial benefits associated with SOC management measures
721 such as reduced tillage or cover crops is limited but important for guiding policy
722 support to encourage their uptake. This study finds that there are considerable
723 differences in farm gross margins across a range of suitable SOC management measures
724 and across a number of representative arable farms in two EU-regions (Scotland, UK;
725 Aragon, Spain). Two measures have been identified for each of the regions that combine
726 the possibility of positive farm gross margin effects with relatively low sensitivity to
727 changes in yield effects and effects on input costs.

728 For Scotland, the most promising measures in terms of gross margin effects are reduced
729 tillage intensity and cover crops. Because reduced tillage intensity shows negative gross
730 margin effects in early years of adoption and cover crops have either small positive or
731 negative effects depending on the magnitude of yield effects and changes in input costs,
732 it is questionable that these measures would be adopted in the absence of financial
733 incentives. The possibility of payments to farmers through for example the Scottish
734 Rural Development Programme should be explored. Because both measures reduce
735 surface run-off, payments could be targeted to areas with greater erosion risk and
736 where arable farming is found to contribute significantly to diffuse water pollution.

737 Fertilisation with animal manures and crop rotations with legumes are the two
738 measures with a promising outlook in terms of gross margin effects for Aragon. Crop

739 rotations (with legumes) is more widely adopted compared to fertilisation with animal
740 manures. While this is unlikely to be entirely attributable to financial incentives, the fact
741 that subsidies are currently available for crop rotations (with legumes) certainly plays a
742 role. Because of the considerable positive effect on gross margins, the advantages and
743 disadvantages of ceasing financial incentives for crop rotations (with legumes) to
744 support other measures such as fertilisation with animal manures should be explored.

745

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1064 **Table S1.** Sensitivity analysis of the SOC scenarios farms in Scotland, UK (corresponding figure: Figure 4)

Scenarios	Farm types	Sensitivity analysis cases											
		YmaxCmax			YmaxCmin			YminCmax			YminCmin		
		2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
CCLeg	Large	-0.017	-0.017	-0.016	0.057	0.060	0.059	-0.030	-0.030	-0.030	-0.004	-0.004	-0.004
	Medium	-0.024	-0.024	-0.023	0.070	0.071	0.070	-0.062	-0.062	-0.062	-0.009	-0.009	-0.009
	Small	-0.024	-0.024	-0.024	0.074	0.075	0.074	-0.066	-0.066	-0.066	-0.011	-0.012	-0.012
CCNoLeg	Large	-0.014	-0.014	-0.014	0.019	0.019	0.018	-0.025	-0.025	-0.025	-0.006	-0.006	-0.006
	Medium	-0.024	-0.024	-0.024	0.029	0.029	0.028	-0.055	-0.055	-0.055	-0.016	-0.016	-0.016
	Small	-0.026	-0.026	-0.025	0.029	0.029	0.028	-0.059	-0.060	-0.059	-0.019	-0.019	-0.019
ZeroTill	Large	0.037	0.060	0.075	0.097	0.126	0.142	-0.155	-0.106	-0.076	-0.109	-0.054	-0.021
	Medium	0.039	0.061	0.075	0.092	0.120	0.135	-0.142	-0.097	-0.068	-0.102	-0.049	-0.018
	Small	0.038	0.060	0.075	0.092	0.120	0.136	-0.147	-0.100	-0.071	-0.106	-0.053	-0.021
RedTill	Large	0.092	0.091	0.091	0.126	0.127	0.127	-0.064	-0.063	-0.063	-0.036	-0.033	-0.033
	Medium	0.086	0.084	0.084	0.120	0.121	0.120	-0.061	-0.060	-0.060	-0.033	-0.030	-0.030
	Small	0.085	0.084	0.084	0.120	0.121	0.120	-0.064	-0.064	-0.064	-0.036	-0.033	-0.033
ResMan	Large	-0.104	-0.054	-0.101	0.062	0.068	0.068	-0.225	-0.220	-0.220	-0.089	-0.082	-0.082
	Medium	-0.104	-0.056	-0.103	0.056	0.062	0.062	-0.216	-0.213	-0.213	-0.085	-0.078	-0.078
	Small	-0.105	-0.060	-0.104	0.055	0.061	0.061	-0.220	-0.218	-0.217	-0.089	-0.082	-0.082

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Table S2. Sensitivity analysis of the SOC scenarios for farms in Aragon, Spain (corresponding figure: Figure 6)

Scenarios	Sensitivity analysis cases											
	YmaxCmax			YmaxCmin			YminCmax			YminCmin		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
CCLeg	0.035	0.035	0.035	0.064	0.064	0.064	-0.142	-0.141	-0.141	-0.045	-0.045	-0.045
CCNoLeg	-0.017	-0.017	-0.017	0.049	0.049	0.049	-0.088	-0.087	-0.087	-0.031	-0.031	-0.031
RedTill	-0.165	0.024	0.151	-0.146	0.056	0.187	-0.341	-0.171	-0.058	-0.326	-0.146	-0.029
ResMan	-0.064	-0.063	-0.063	-0.029	-0.025	-0.025	-0.043	-0.042	-0.042	-0.042	-0.039	-0.039
FertMan	0.270	0.268	0.268	0.309	0.307	0.307	0.034	0.034	0.034	0.065	0.064	0.064
OptFert	0.312	0.309	0.309	0.320	0.326	0.325	-0.272	-0.271	-0.271	-0.268	-0.262	-0.262
CRot	0.422	0.424	0.423	0.427	0.437	0.437	0.168	0.170	0.170	0.171	0.179	0.179

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